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Digital neutron-gamma discrimination in a wide energy range using pulse reconstruction method

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HIGHLIGHTS

- The pulse reconstruction method was utilized to perform neutron-gamma discrimination (NGD) with NE213 scintillator.
- A digital storage oscilloscope with an 8-bit digital-to-analog convertor was responsible for receiving the scintillator anode pulses.
- The NGD results on an Am–Be combined neutron-gamma source represents the feasibility of the proposed method.

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ABSTRACT

In this research, based on pulse reconstruction method, digital storage oscilloscopes with an 8-bit digital-to-analog convertor was used to successfully perform the neutron-gamma discrimination with NE213 (or its equivalent BC501A) scintillator anode pulses at minimum discrimination bias value of 95 keVee (or keV electron equivalent). Also, a 100 mCi ^{241}Am–Be source and micro-Curie gamma ray sources (^{137}Cs and ^{22}Na) were used for the system calibration and discrimination studies. The results confirm the feasibility and simplicity of the proposed method.

1. Introduction

Gamma rays are always accompanying neutrons in isotopic neutron sources which reinforce the importance of neutron-gamma discrimination (NGD) techniques (Knoll, 2010). The NGD has important applications in neutron flux/spectrum determination in heavy ion therapeutic systems, fast neutron (above tens of MeVs) production in spallation reactions (Yoshioka, 2011) and photoneutrons of about 1 MeV energy produced as a result of high-energy (above 12 MeV) X-ray interactions in medical linear accelerators (Esposito et al., 2008). A variety of NGD techniques such as zero-cross, Owen, time-of-flight, and charge comparison methods have been frequently used by many researchers around the world (Divani-Vais et al., 2012; Binaei Bash et al., 2013). The digital discrimination systems introduced and significantly developed in recent years have found numerous applications and they show many advantages over analog systems. The reduction in the size of required electronics, multi-parameter analysis feature, high-compatibility with other hardware, enhanced efficiency, stability and manageability are the most important advantages (Siddavatam, 2014).

Both anode and dynode pulses can be used for discrimination process, however anode pulses result in more efficient and precise pulse-shape discrimination (PSD). The end region of decay time is a characteristic of radiation type in fast anode pulses (i.e., with 50 Ω load resistor) (Cvachovec, 2011). Fig. 1 shows two anode pulses of NE213 scintillator when exposed to neutrons and gamma rays representing different decay times.

The digital NGD with anode pulses, when performed in wide energy range and especially in low-energy, requires a fast analog-to-digital convertor (ADC) with 12-bit or higher precision. The design and fabrication of such electronic circuitry is complex and costly.

Some researchers prefer to use 8-bit ADCs which take

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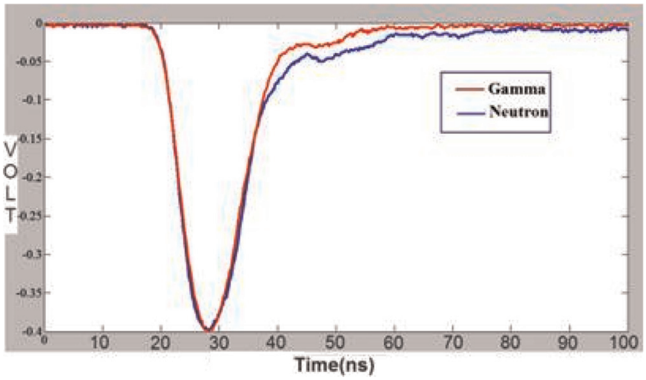

Fig. 1. The anode pulses of an NE213 scintillator when exposed to neutrons and gamma rays.

advantage of simple driving circuit but these ADCs are basically unable to cover wide range of energies because when the circuit operates in high-gain mode, large-amplitude pulses saturate giving no clear peak magnitude. On the other hand, when using these ADCs in low-gain mode, the discrimination factor weakens for low-amplitude pulses (Takaku and Baba, 2011). In the present study, it has been tried to perform the neutron-gamma discrimination in wide dynamic range of pulses using an 8-bit ADC and by incorporating pulse reconstruction method.

2. Materials and methods

The setup of Fig. 2 has been used for the NGD measurements. The detector includes a ∅3 in. × 3 in. cylindrical aluminum cell of NE213 scintillator, optically coupled to a 3 in. R6091 HAMAMATSU photomultiplier tube (PMT) covered with a thin mu-metal cylinder and jointed to a resistor voltage divider. A 100 mCi ^{241}Am–Be neutron source in paraffin wax as moderator has been used for the NGD measurements whilst the energy calibration has been undertaken with 0.5 μCi and 2 μCi ^{137}Cs and ^{22}Na gamma-ray sources, respectively. The digital sampling of anode pulses has been performed with an 8-bit 500 MHz–5 Gs/s digital storage oscilloscope.

The anode pulse has been digitized and each pulse is stored in the form of a two-column time-amplitude matrix such that all characteristics including rise-time, fall time, amplitude etc. can be extracted. The number of rows is apparently dependent on the oscilloscope timing resolution. In this research, according to the required precision and the data acquisition/storage/processing speed, it has been decided to select 500 points for each pulse. A computer software, specifically written in C#, has been prepared for the data processing of the present study. The software takes average on every 10 points to reduce noise and consequently smooth the pulse.

In order to determine the best discrimination quality, different

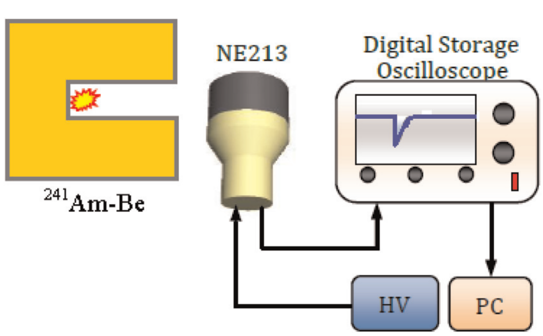

Fig. 2. A schematic of experimental setup for digital NGD.

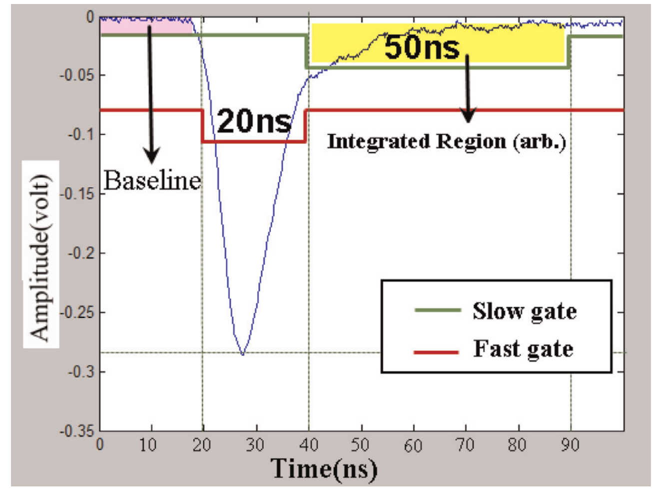

Fig. 3. A time gate used for sampling from anode pulses with pulse-heights reaching to 10% of maximum amplitudes.

parameters of anode pulses have been experimentally studied. It has been finally decided to take the area under the decay region in the time interval shown in Fig. 3, up to 10% of pulse amplitude as recommended by Yoshioka (2011). The NGD curve can be produced by plotting the above integration in terms of peak amplitude. By decreasing the volt division of oscilloscope, the procedure can be performed for low-amplitude pulses, and hence the discrimination is achievable for very small thresholds. But as shown in Fig. 4, small volt divisions result in the saturation of pulses which prevents recording the pulse amplitudes. This problem can be resolved by fitting an appropriate curve to the points which are in unsaturated region of the pulse.

The anode pulse function can be calculated in two different ways: (1) using scintillation light yield curves for different charged particles (Cvachovec, 2011) and the PMT equivalent circuit or (2) using data fitting on several pulses and determination of pulse function.

The precise calculation of pulse function based on PMT equivalent circuit and scintillator behavior is relatively difficult due to numerous capacitors and inductors of such acquisition device. Then, the fitting process has been undertaken with complex function feature of MATLAB software and after some try and error it has been decided to implement the following third-order Gaussian function for data fitting on a sampled anode pulse:

$$F(x) = k\left(a_1 e^{-\left(\frac{x-b1}{c1}\right)^2} + a_2 e^{-\left(\frac{x-b2}{c2}\right)^2} + a_3 e^{-\left(\frac{x-b3}{c3}\right)^2}\right) \quad (1)$$

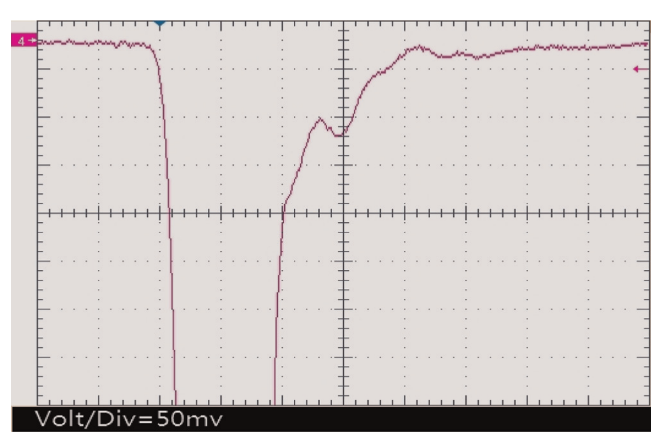

Fig. 4. The saturated anode pulse of an NE213 scintillator.

Table 1
Fitting parameters used for fitting a third-order Gaussian function on a sampled anode pulse.

Parameter	Value
a_1	−0.3057
b_1	18.9800
c_1	15.4400
a_2	−0.1348
b_2	38.6600
c_2	14.8600
a_3	−0.5671
b_3	41.1400
c_3	33.6700
k	1 (varies with pulse amplitude)

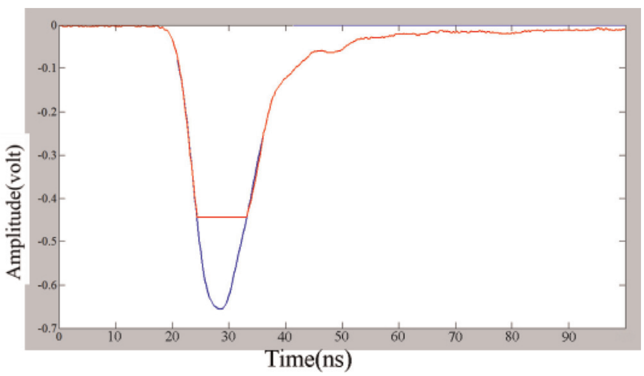

Fig. 5. The construction of saturated anode pulse using a third-order Gaussian data fitting.

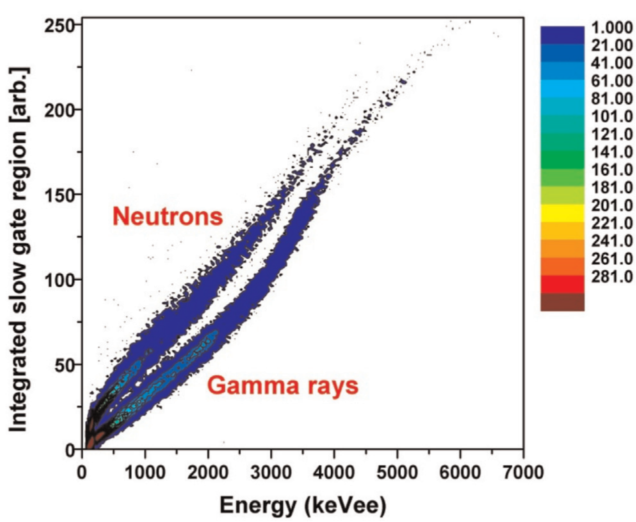

Fig. 6. A three-dimensional representation of the NGD performed with an NE213 scintillator exposed to ^{241}Am–Be source.

For determining parameters of this function, a number of pulses with amplitudes larger than 450 mV and with the oscilloscope reference voltage of 800 mV have been recorded. Then, by using a fitting program in MATLAB which varies the parameters of fitting model to achieve the best goodness-of-fit on upper 80% amplitude of anode pulse, the parameters have been obtained as listed in Table 1. The accuracy of fitting parameters is normally verified by repeating the above procedure for a large number of unsaturated pulses.

By selecting appropriate value for k parameter, the anode pulse function with any amplitude, regardless of whether saturated or unsaturated type can be derived. A program in C# language has

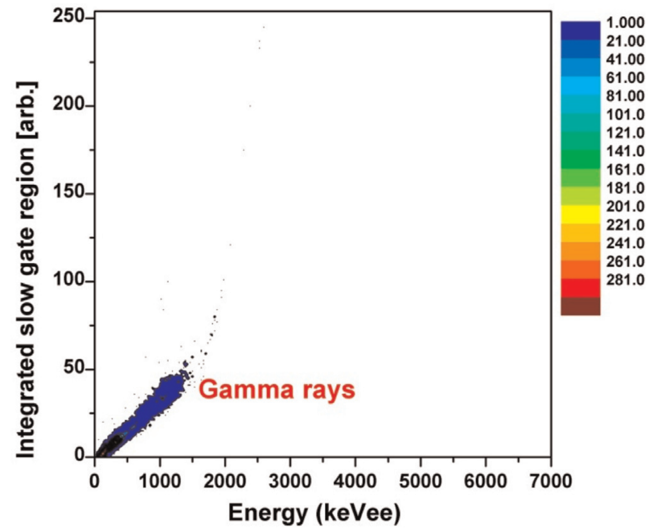

Fig. 7. A three-dimensional representation of the NGD performed with an NE213 scintillator exposed to ^{22}Na gamma-ray source.

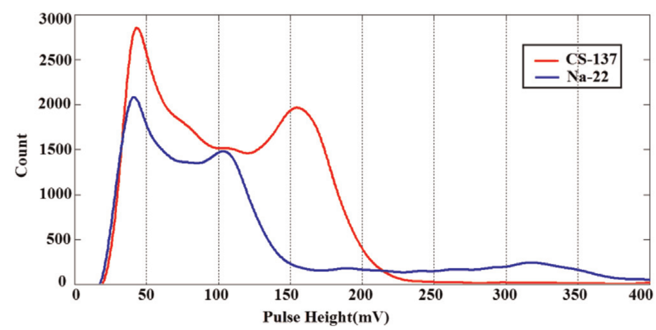

Fig. 8. The NE213 scintillator spectra when exposed to ^{137}Cs and ^{22}Na gamma-ray sources.

been written, for extracting the information of unsaturated pulses as well as identifying and modeling (i.e., curve-fitting on) saturated pulses. The program then returns both the time characteristics and amplitudes of constructed pulses. Since the difference between the neutron and gamma pulses is mostly within 10% of peak amplitude, only the data points with amplitudes greater than 200 mV are used for fitting process and determining k parameter. A sample constructed saturated pulse is shown in Fig. 5.

Having prepared the algorithm for pulse reconstruction, the data acquisition has been performed with an NE213 scintillator exposed to ^{241}Am–Be neutron source, from which the reference voltage of 450 mV have been chosen with oscilloscope.

In order to determine the discrimination threshold, the energy calibration has been performed with two gamma ray sources (^{137}Cs and ^{22}Na) by recording an appropriate number of anode pulses. The pulse-height spectrum can obtained by plotting the pulse maxima against number of pulses (i.e., counts) as illustrated in Fig. 6. By a straight line fitting on the pulse amplitude at Compton edges for gamma-ray energies of 662 keV and 1274 keV the calibration equation can be extracted in keV/mV unit.

The neutron-gamma discrimination quality is normally expressed by FOM (Figure of Merit) as:

$$\mathrm{FOM} = S/(\mathrm{FWHM}_\gamma + \mathrm{FWHM}_\mathrm{n}) \tag{2}$$

where S and FWHM are the separation distance and the full-width at half maxima of neutron and gamma peaks, respectively (Zare et al., 2013).

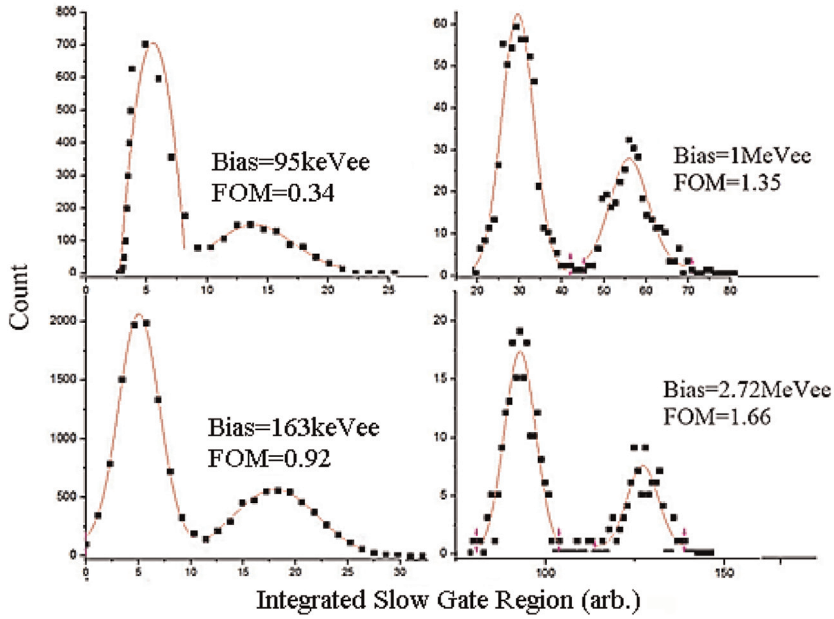

Fig. 9. The NGD two-dimensional spectra at different discrimination biases performed with an NE213 scintillator exposed to ^{241}Am–Be source.

3. Results and discussions

Fig. 6 illustrates a three-dimensional representation of the NGD performed with pulse reconstruction method whilst Fig. 7 shows the NGD spectrum when the ^{241}Am–Be source has been replaced with a ^{22}Na gamma-ray source which has led to a totally empty neutron region.

The energy calibration has been performed using the ^{137}Cs and ^{22}Na spectra shown in Fig. 8. Fig. 9 shows the digital NGD for different discrimination biases undertaken with NE213 scintillator exposed to ^{241}Am–Be source using pulse reconstruction method. As it can be seen, the NGD has been successfully achieved even at low-energy region

According to the volt division of oscilloscope, the maximum pulse-height of 400 mV is corresponding to 1.4 MeV which can be fully recordable. However, when using the pulse reconstruction method, as seen in Fig. 6, the pulses have been recoded up to about 7 MeV. The scintillation light produced by heavy-charged particles and electrons in NE213 as a result of neutron and gamma-ray interactions can be derived through Cecil and Verbinski formulas discussed in Tajik et al. (2013). Following these formulas, one may expect that the Am–Be neutron lights will not exceed 6 MeV and the gamma-rays either from the de-excitation of ^{13}C* nuclei (with 4.43 MeV energy) or as a result of neutron interactions with scintillator housing reaches maximum to 7 MeV.

4. Conclusions

In this study, the NGD has been performed with an NE213 scintillator using an 8-bit ADC and a fast storage oscilloscope based on pulse reconstruction method represented promising results even at low discrimination biases. The NDG for discrimination biases less than 95 keVee requires a careful modification of voltage dividers. This study also confirms that low-resolution ADCs can be used for the NGD with the anode pulses which facilitates the required electronic circuitry.

However, note should be taken that the comparison study between analog and digital NGD may be undertaken using a precise neutron spectrum unfolding code in which both analog and digital NGD pulse-heights taken from an NE213 scintillator exposed to a known neutron source are considered as input data. Since, the digital acquisition results in better discrimination data due to the variety of interesting algorithms that can be applied whilst analog acquisition requires fixed, difficult-to-make circuits, and so forth, one may expect a better unfolded neutron spectrum from digital NGD data. The application of different neutron spectrum unfolding codes on analog and digital NGD spectra and their inter-comparison are still being investigated.

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